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Lee et al.

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(54) **FINFETS WITH DIFFERENT FIN HEIGHTS**

(71) Applicant: **Taiwan Semiconductor Manufacturing Company, Ltd.**, Hsin-Chu (TW)

(72) Inventors: **Tsung-Lin Lee**, Hsin-Chu (TW); **Chih Chieh Yeh**, Taipei (TW); **Chang-Yun Chang**, Taipei (TW); **Feng Yuan**, Hsin-Chu (TW)

(73) Assignee: **Taiwan Semiconductor Manufacturing Company, Ltd.**, Hsin-Chu (TW)

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H01L 27/088 (2006.01)

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21/823437 (2013.01); **H01L 21/823481** (2013.01); **H01L 27/0886** (2013.01); **H01L 27/1104** (2013.01); **H01L 27/1116** (2013.01); **H01L 29/66795** (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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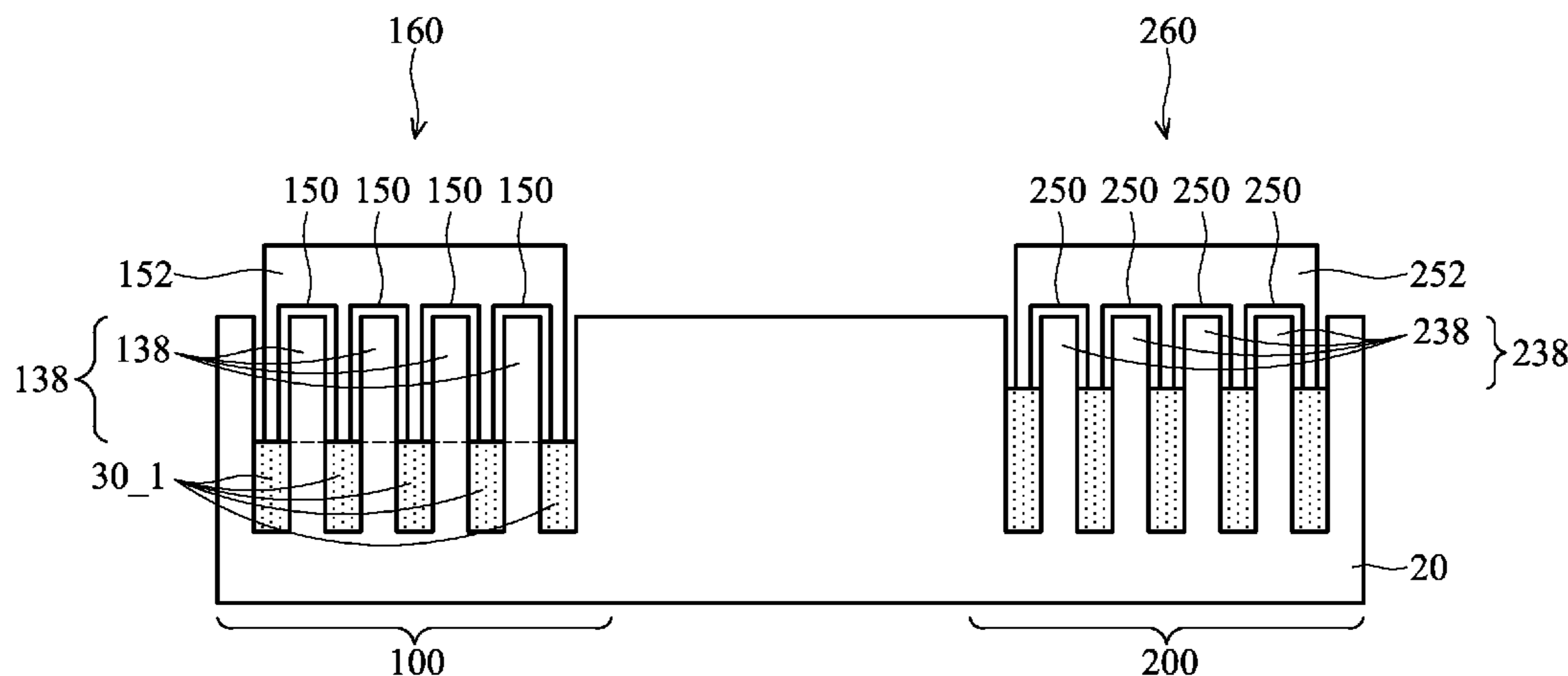
Primary Examiner — Fei Fei Yeung Lopez

(74) *Attorney, Agent, or Firm* — Slater Matsil, LLP

(57) **ABSTRACT**

An integrated circuit structure includes a semiconductor substrate including a first portion in a first device region, and a second portion in a second device region. A first semiconductor fin is over the semiconductor substrate and has a first fin height. A second semiconductor fin is over the semiconductor substrate and has a second fin height. The first fin height is greater than the second fin height.

20 Claims, 17 Drawing Sheets



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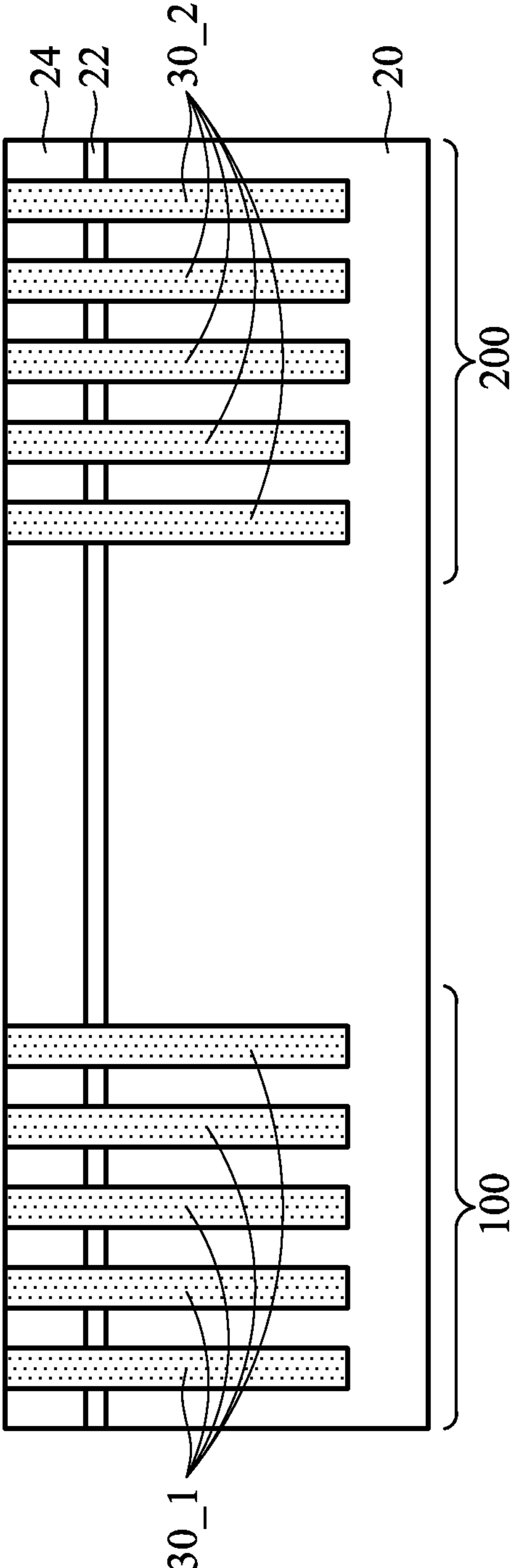


FIG. 1

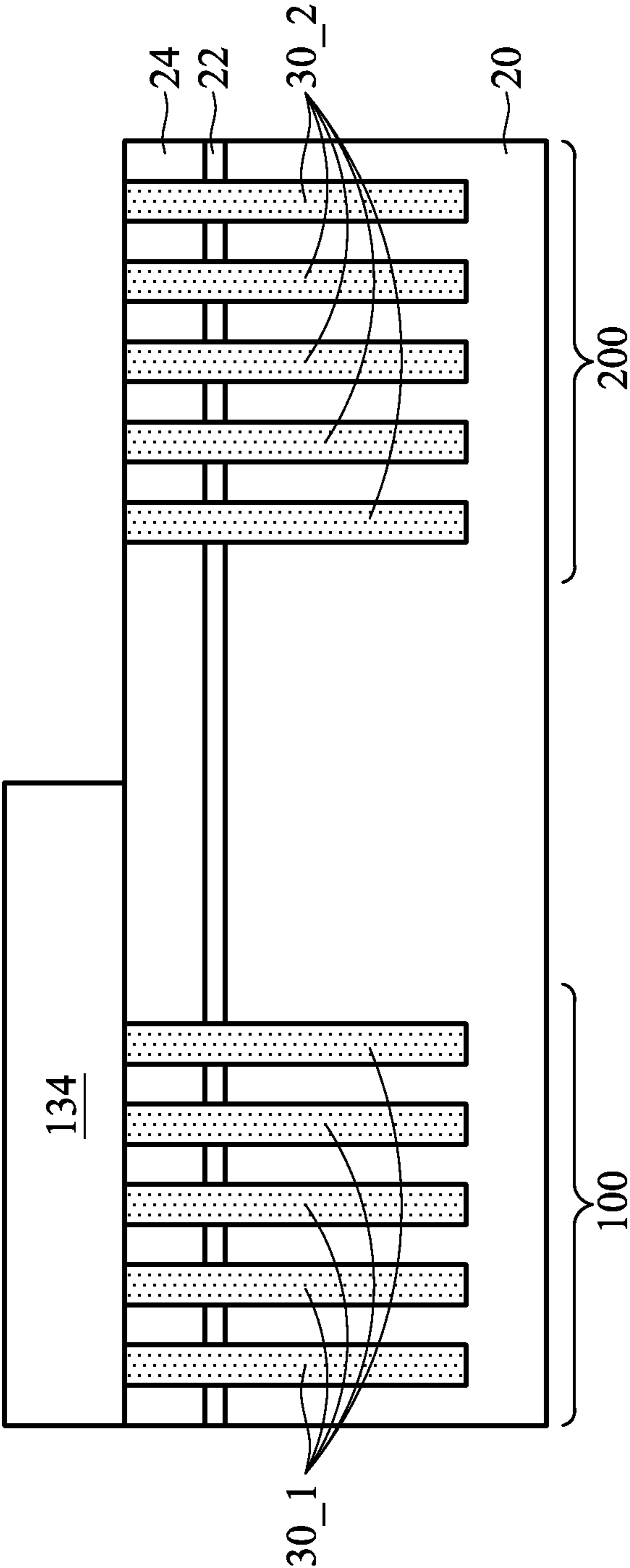


FIG. 2

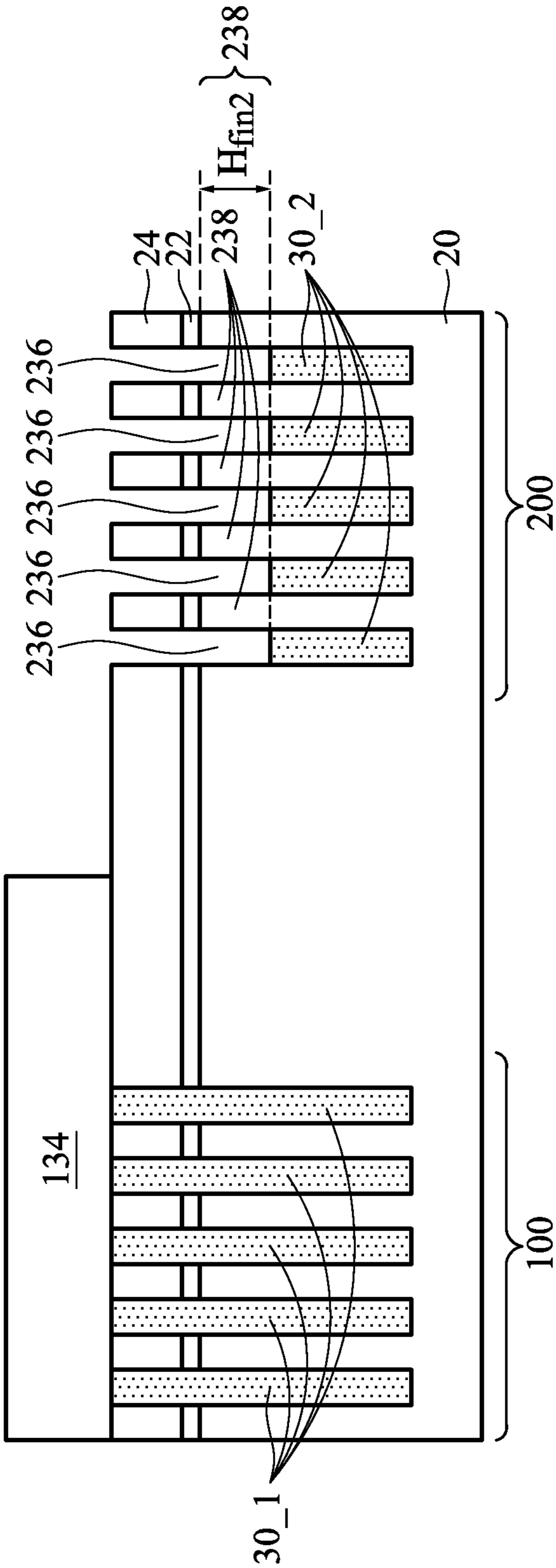


FIG. 3

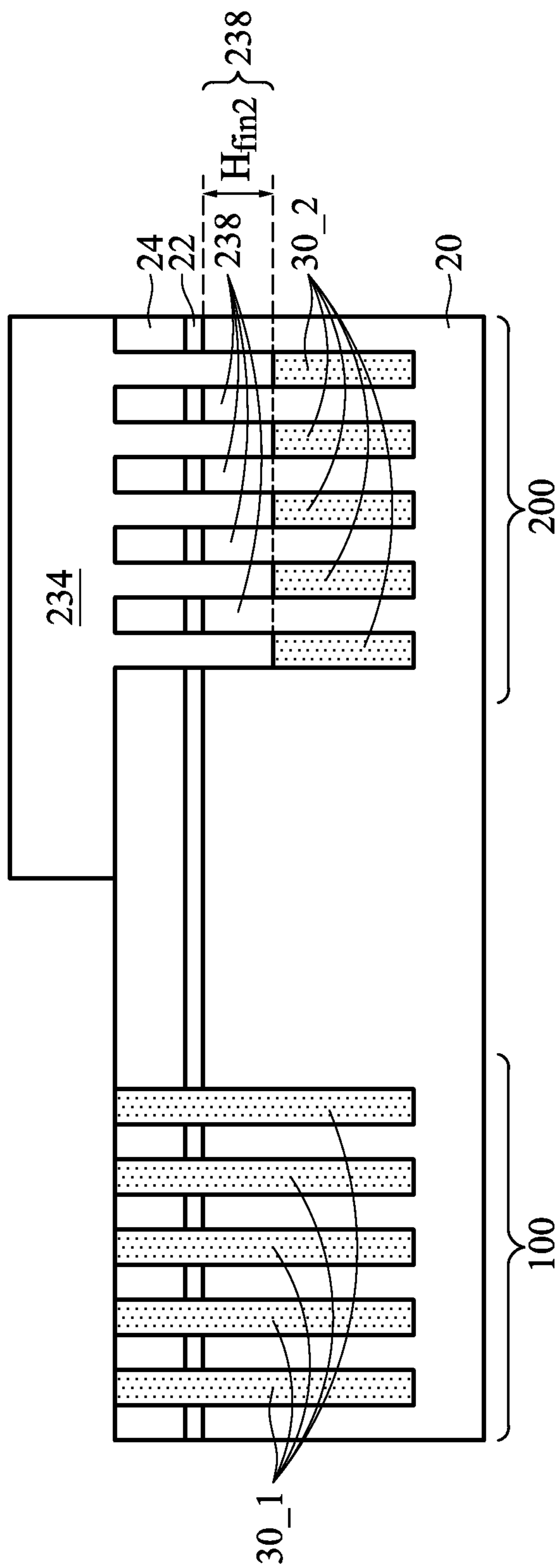


FIG. 4

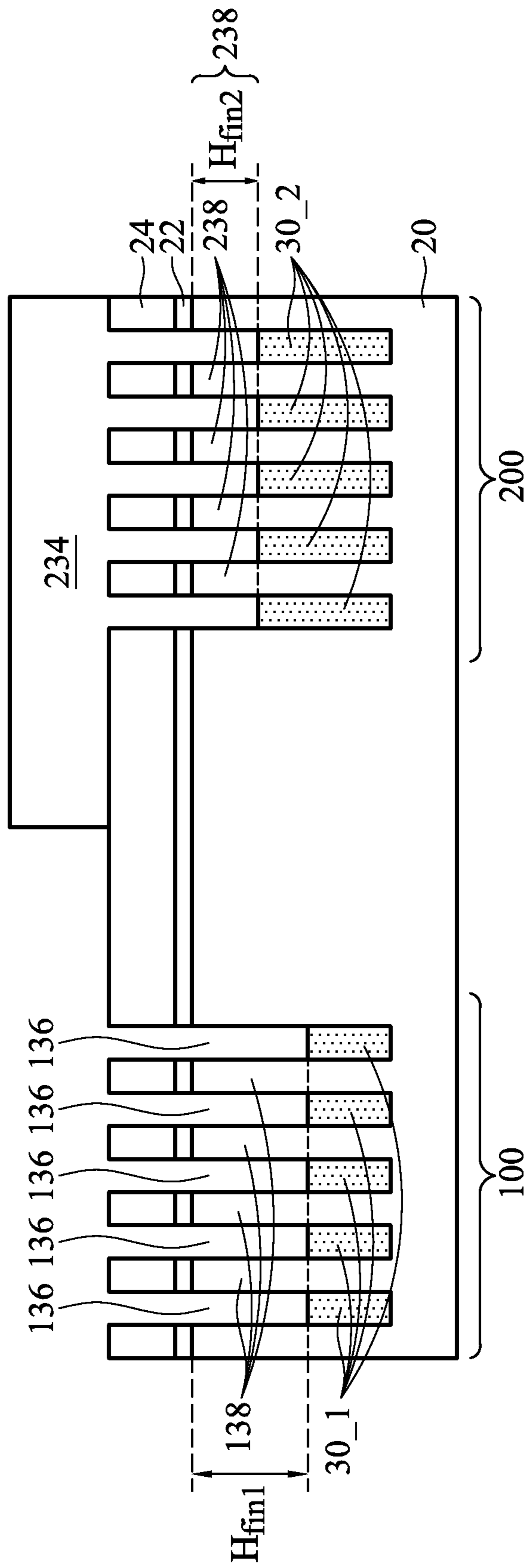


FIG. 5

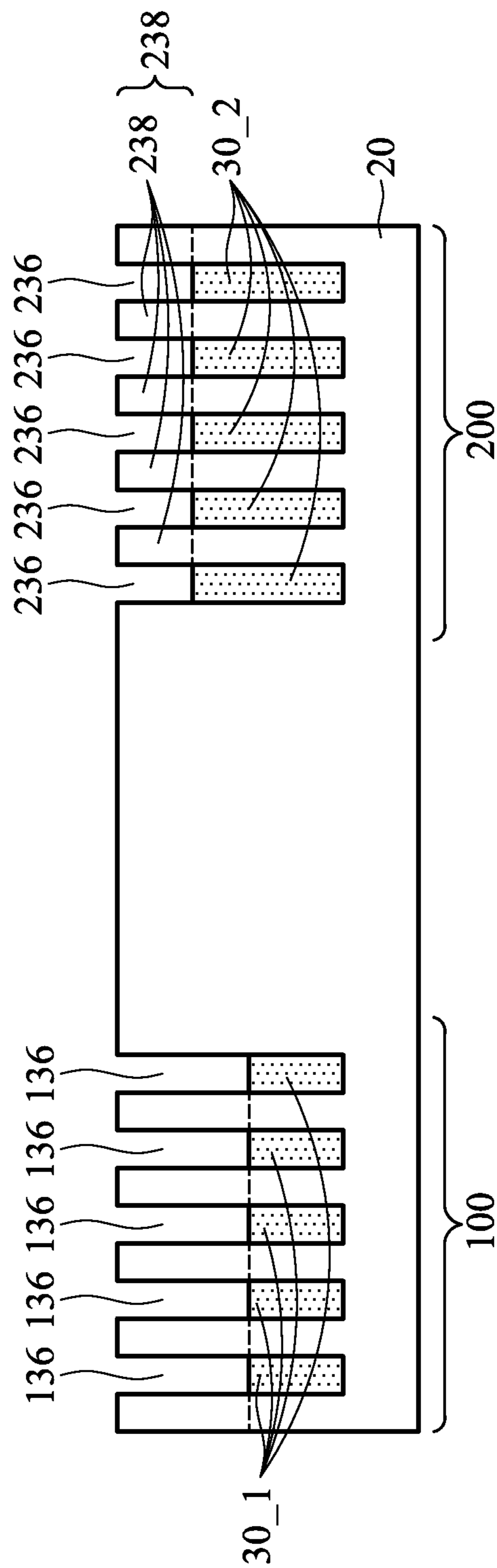


FIG. 6

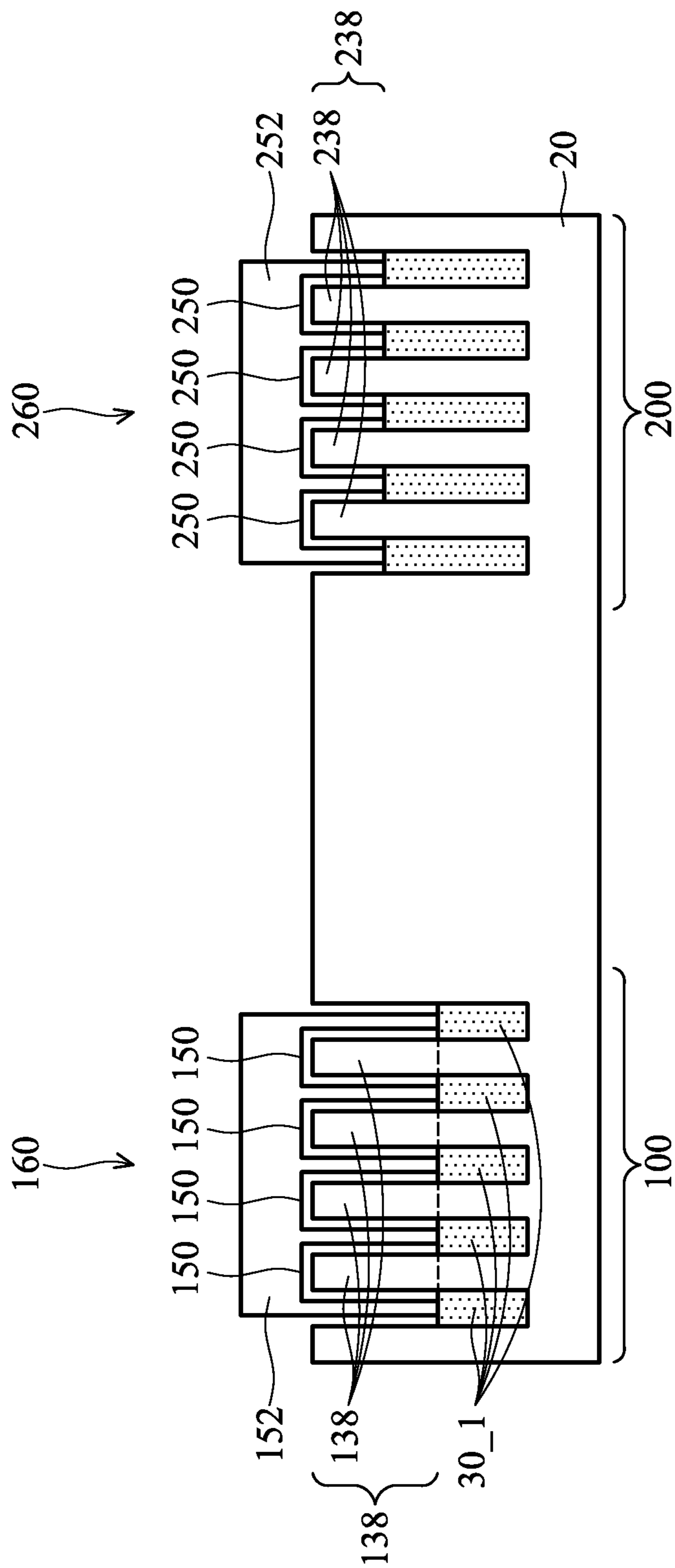


FIG. 7

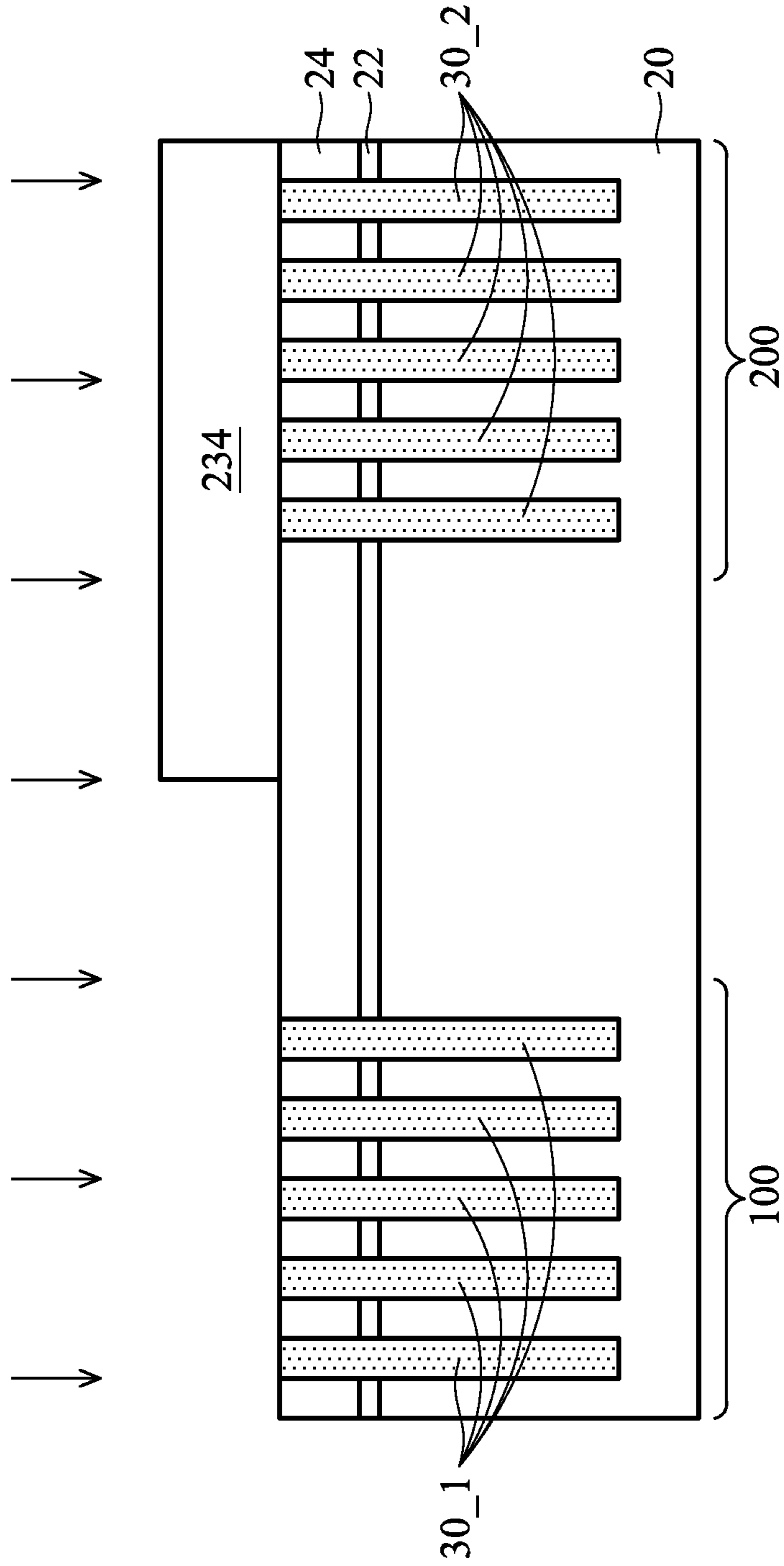


FIG. 8

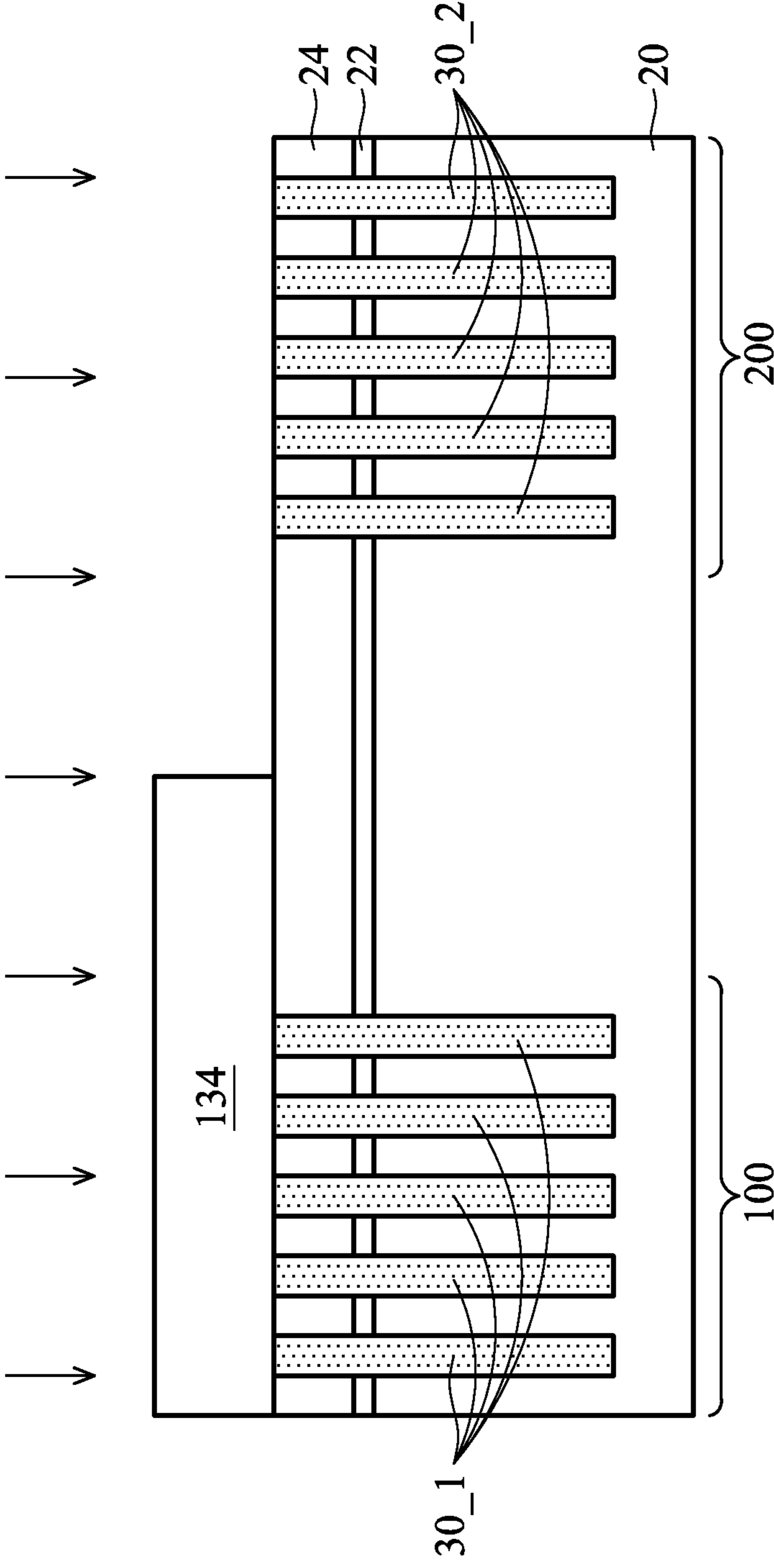


FIG. 9

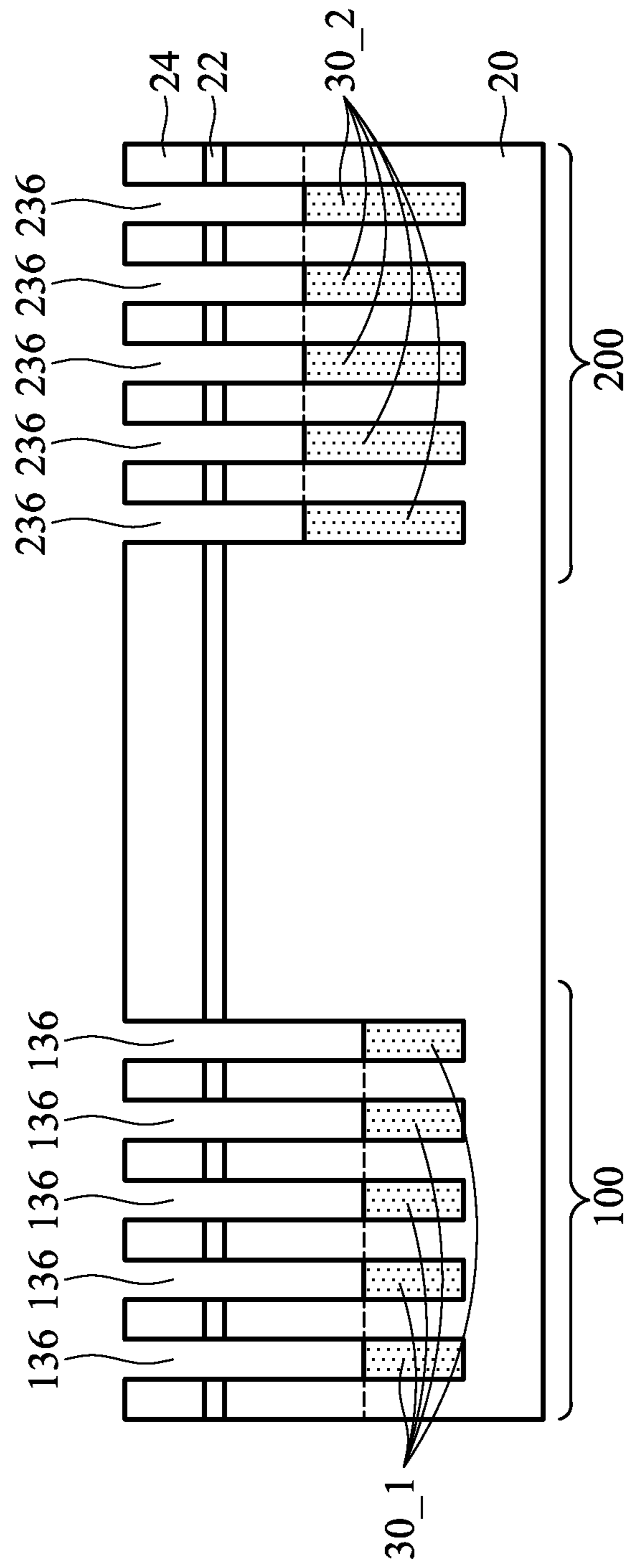


FIG. 10

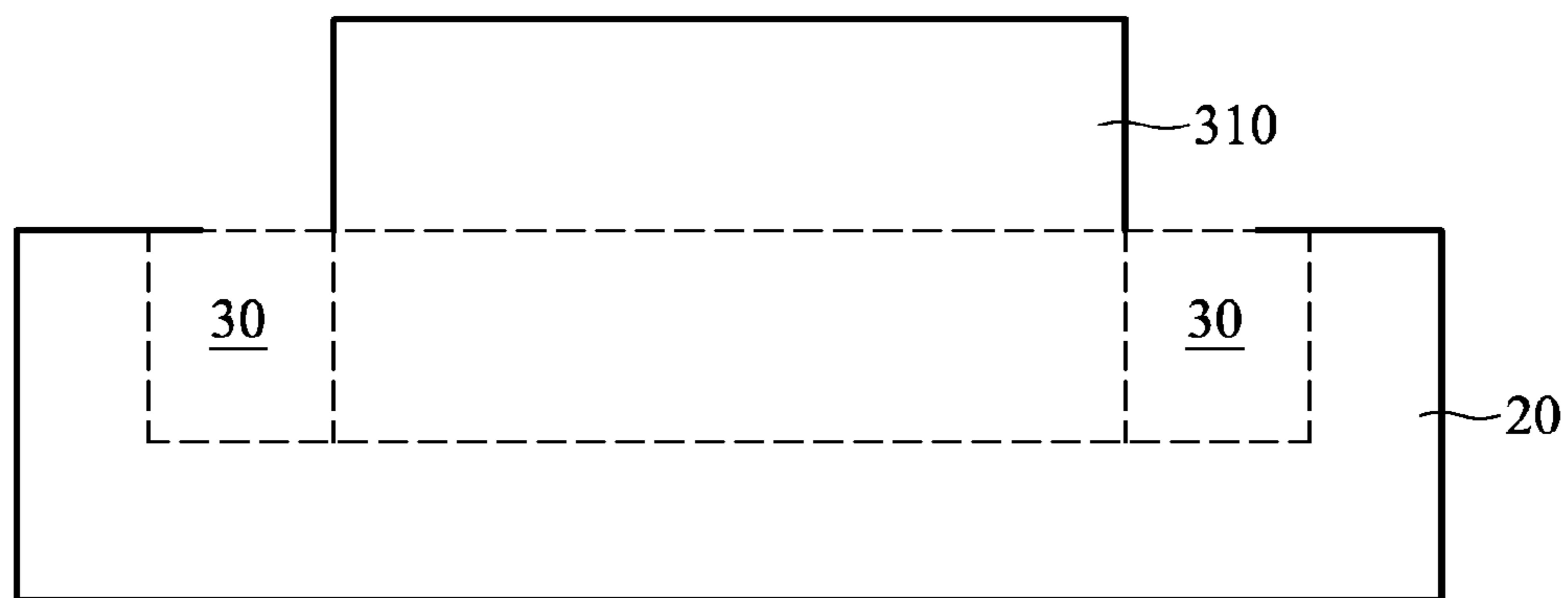


FIG. 11A

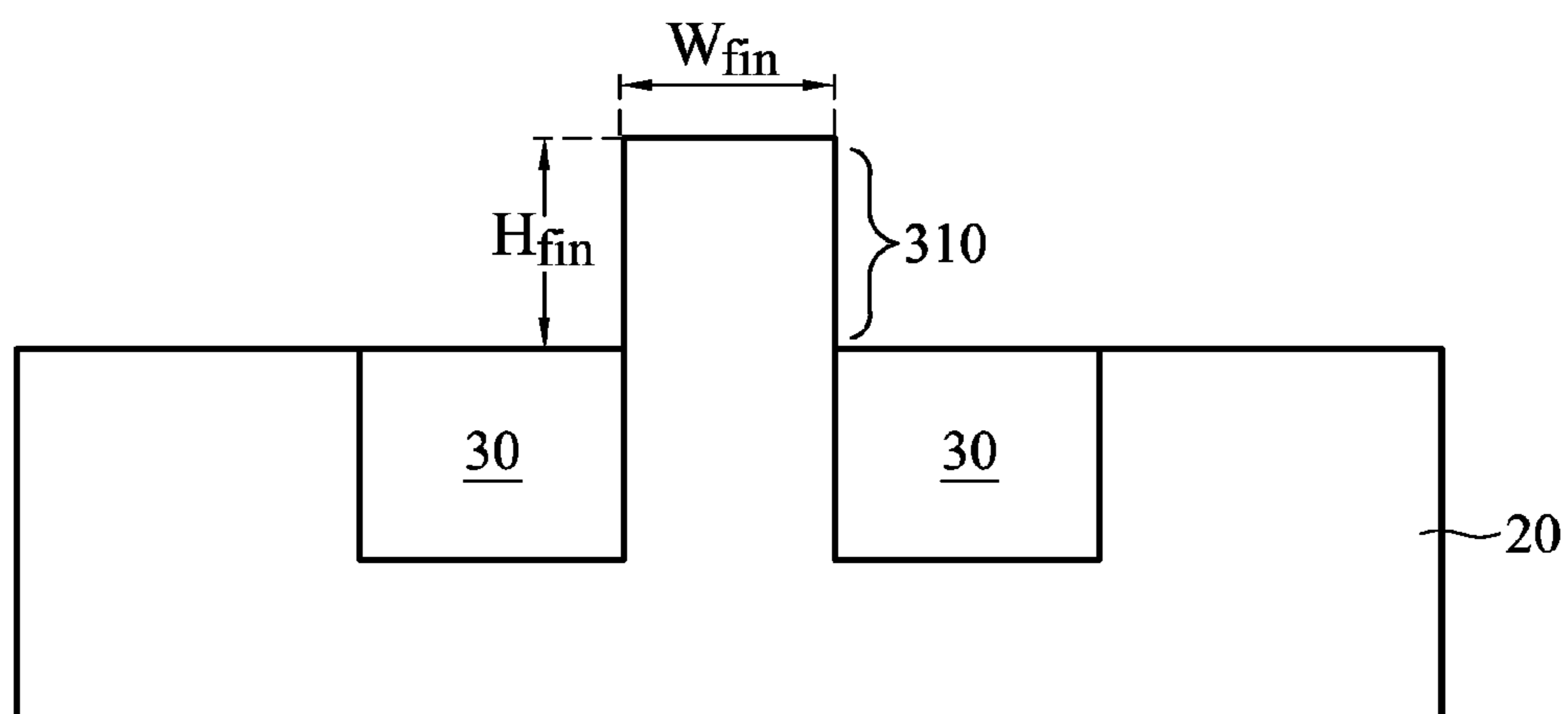


FIG. 11B

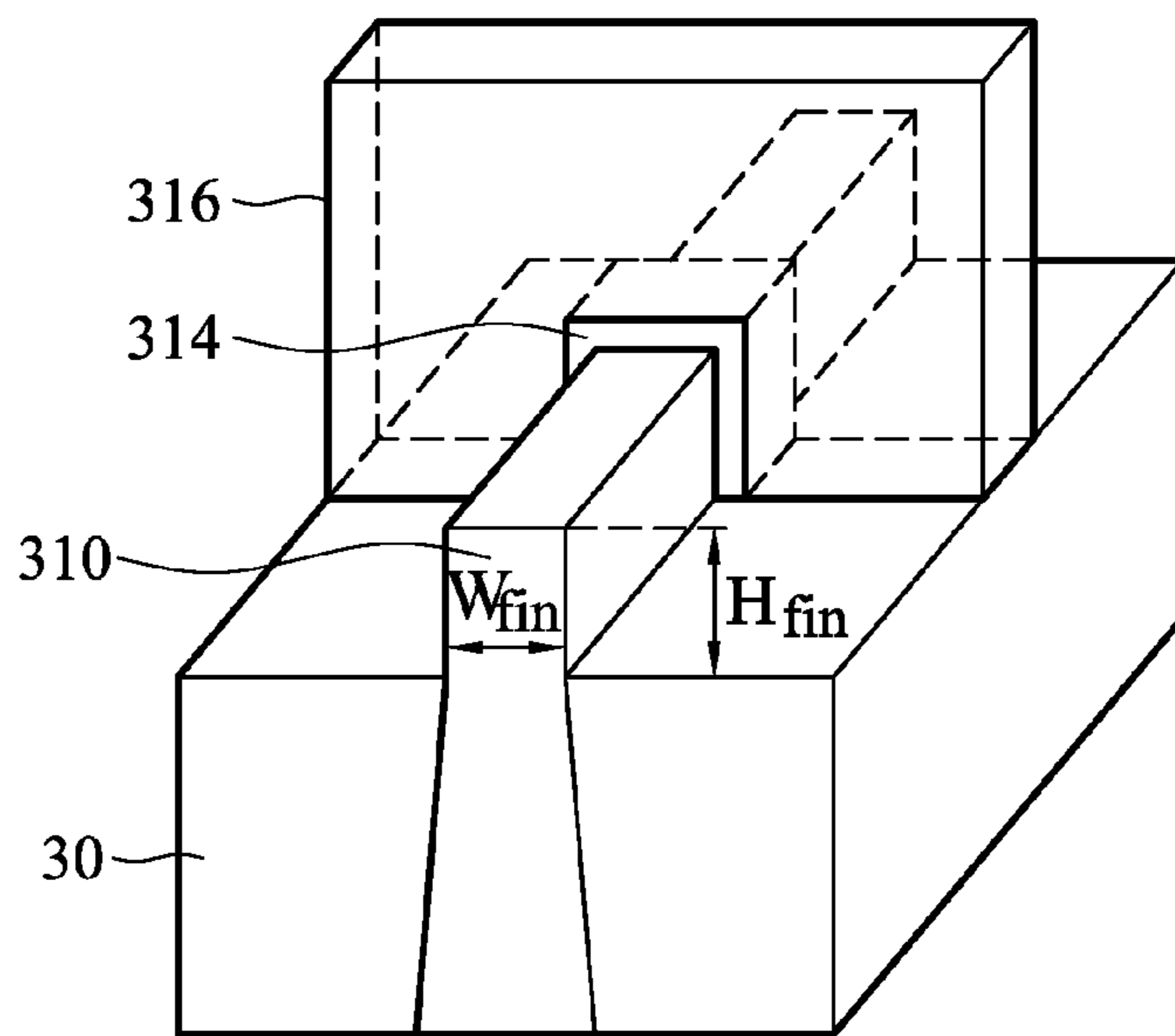


FIG. 12

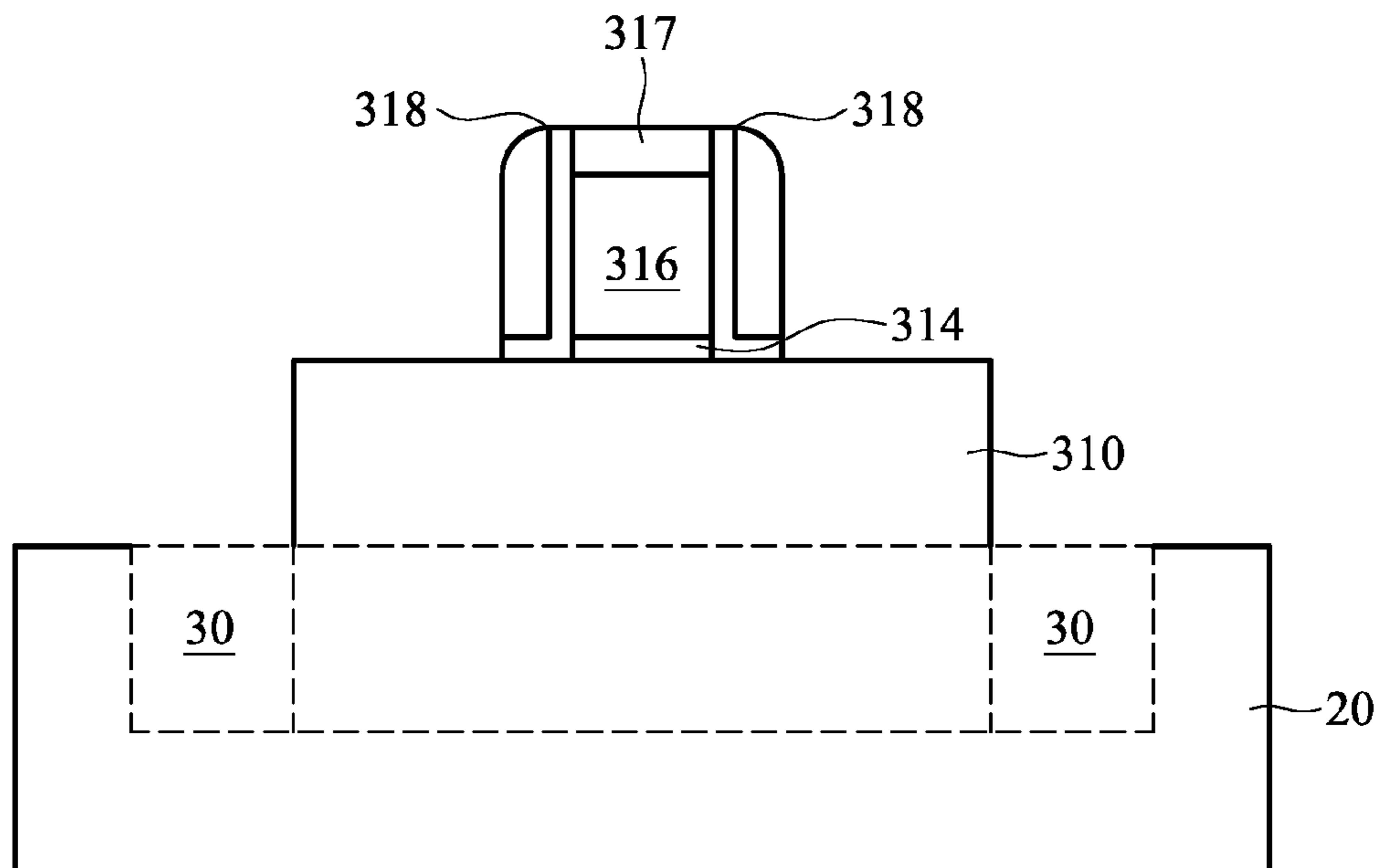


FIG. 13

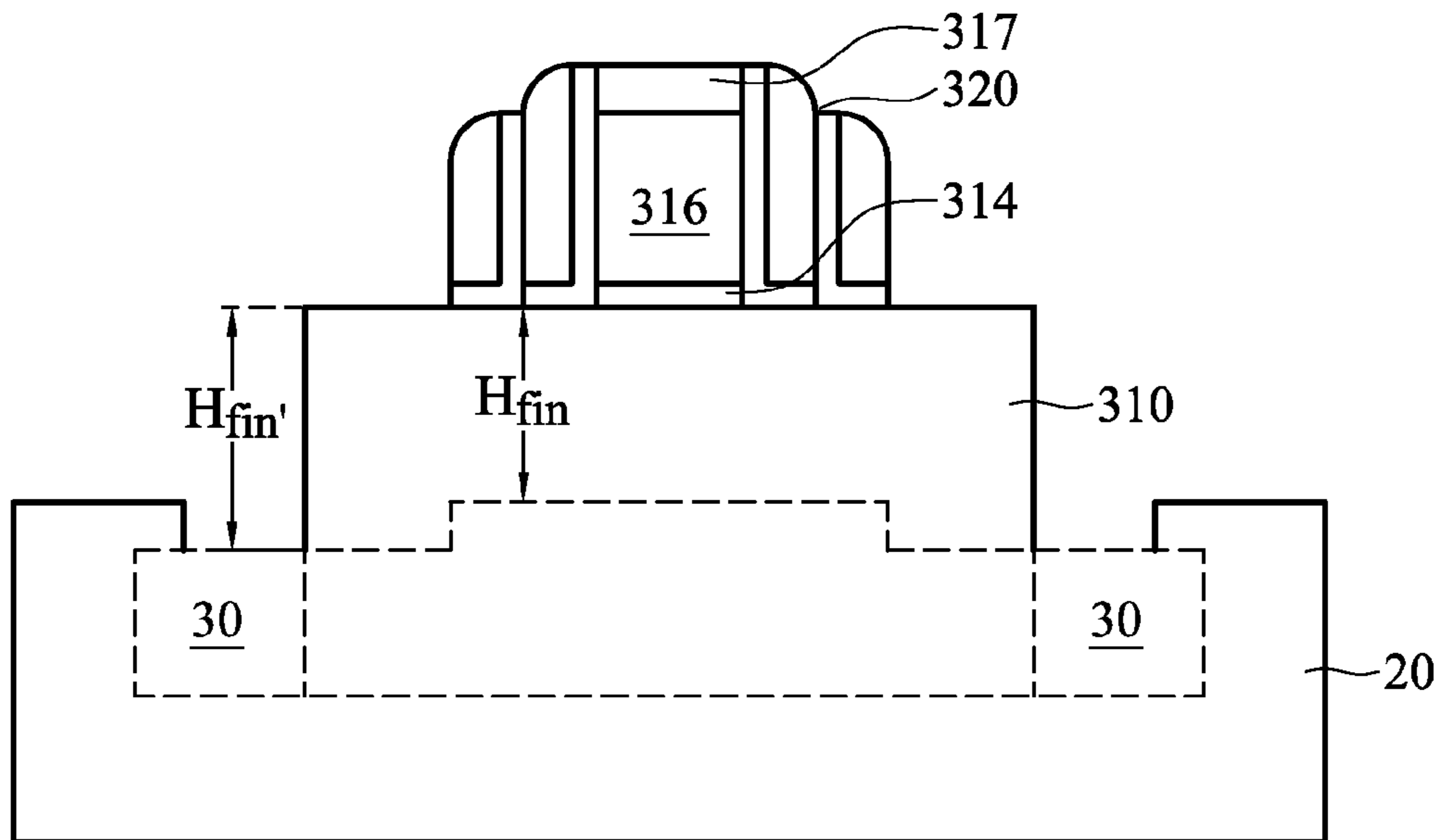


FIG. 14A

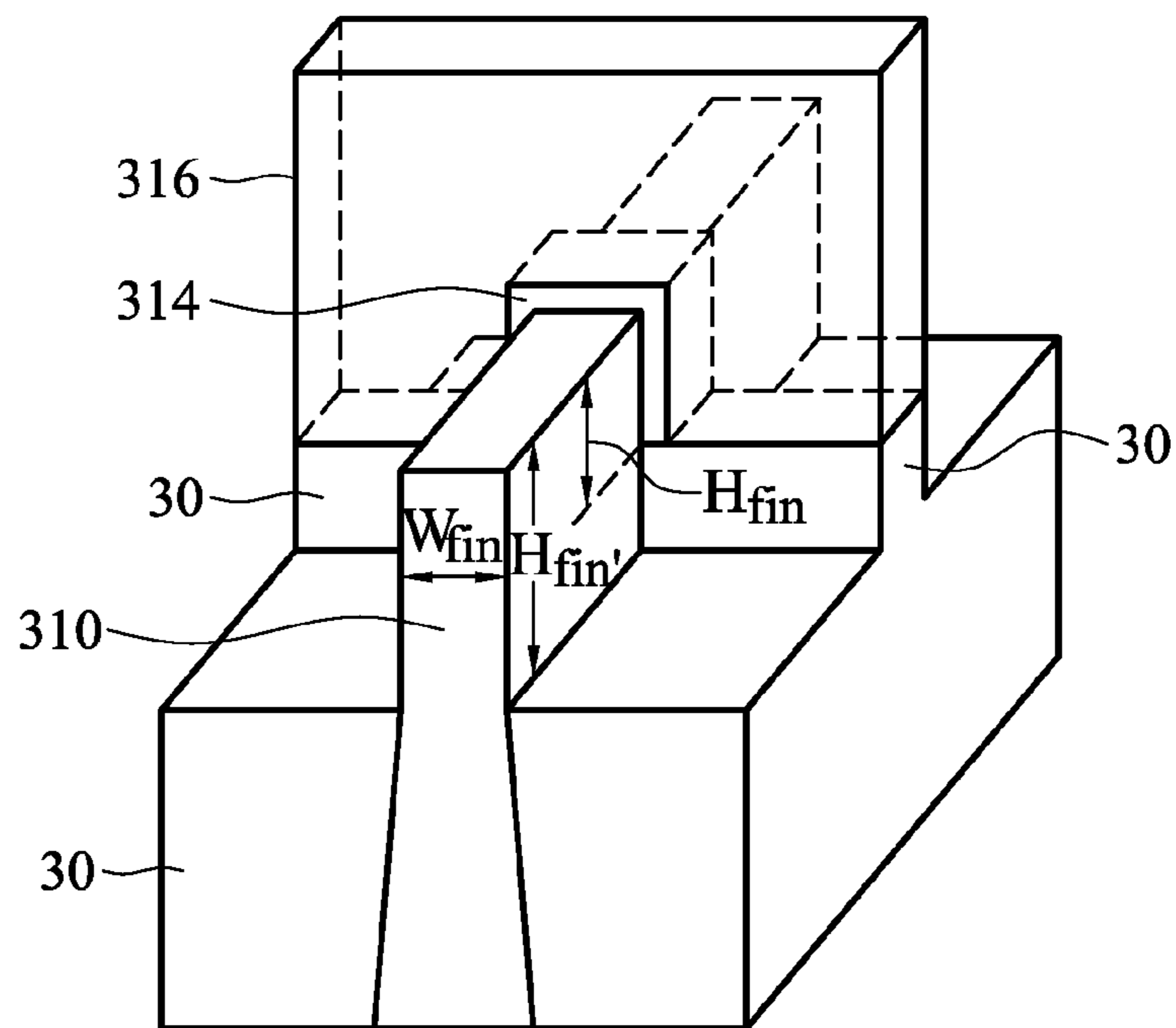


FIG. 14B

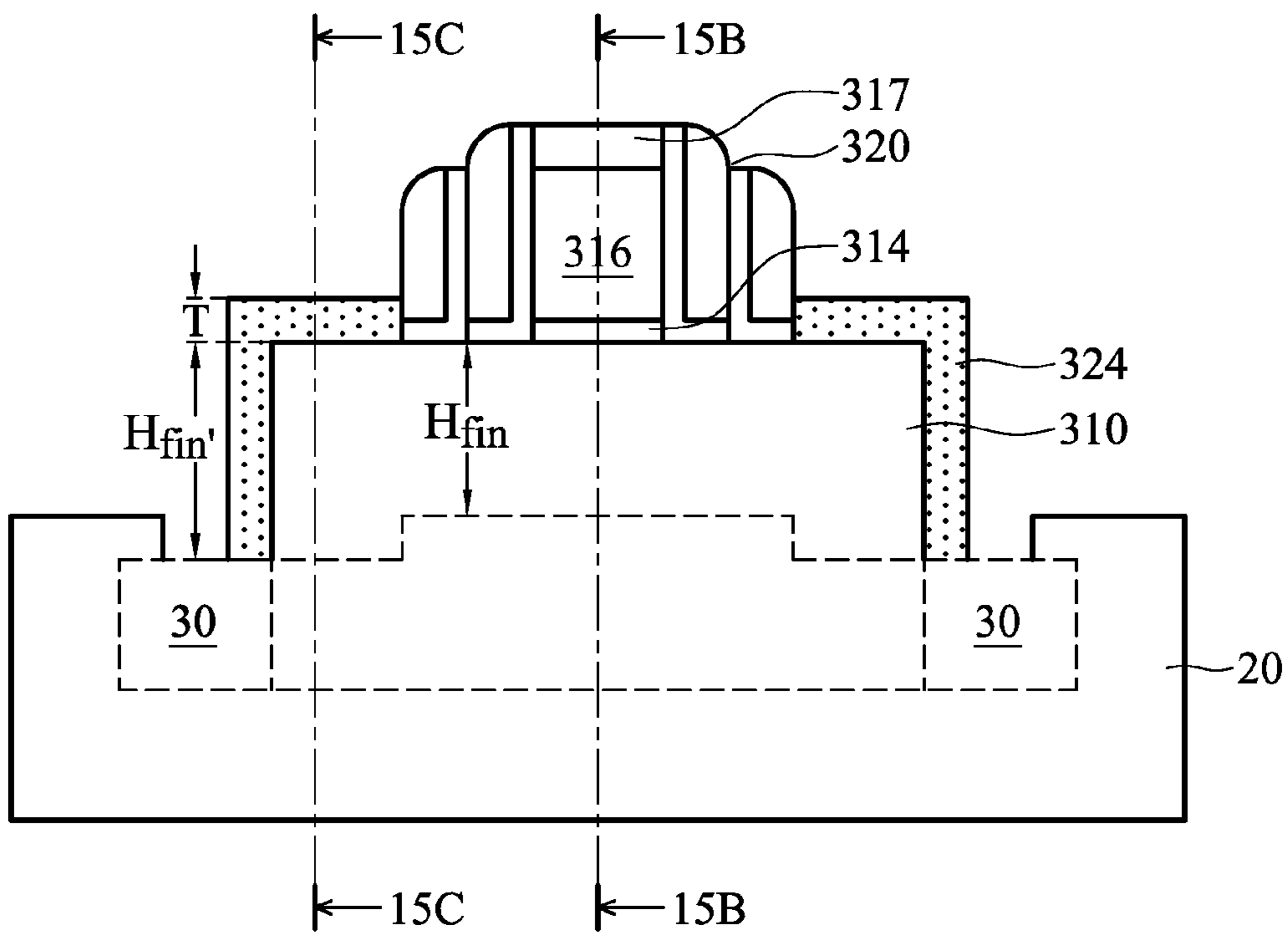


FIG. 15A

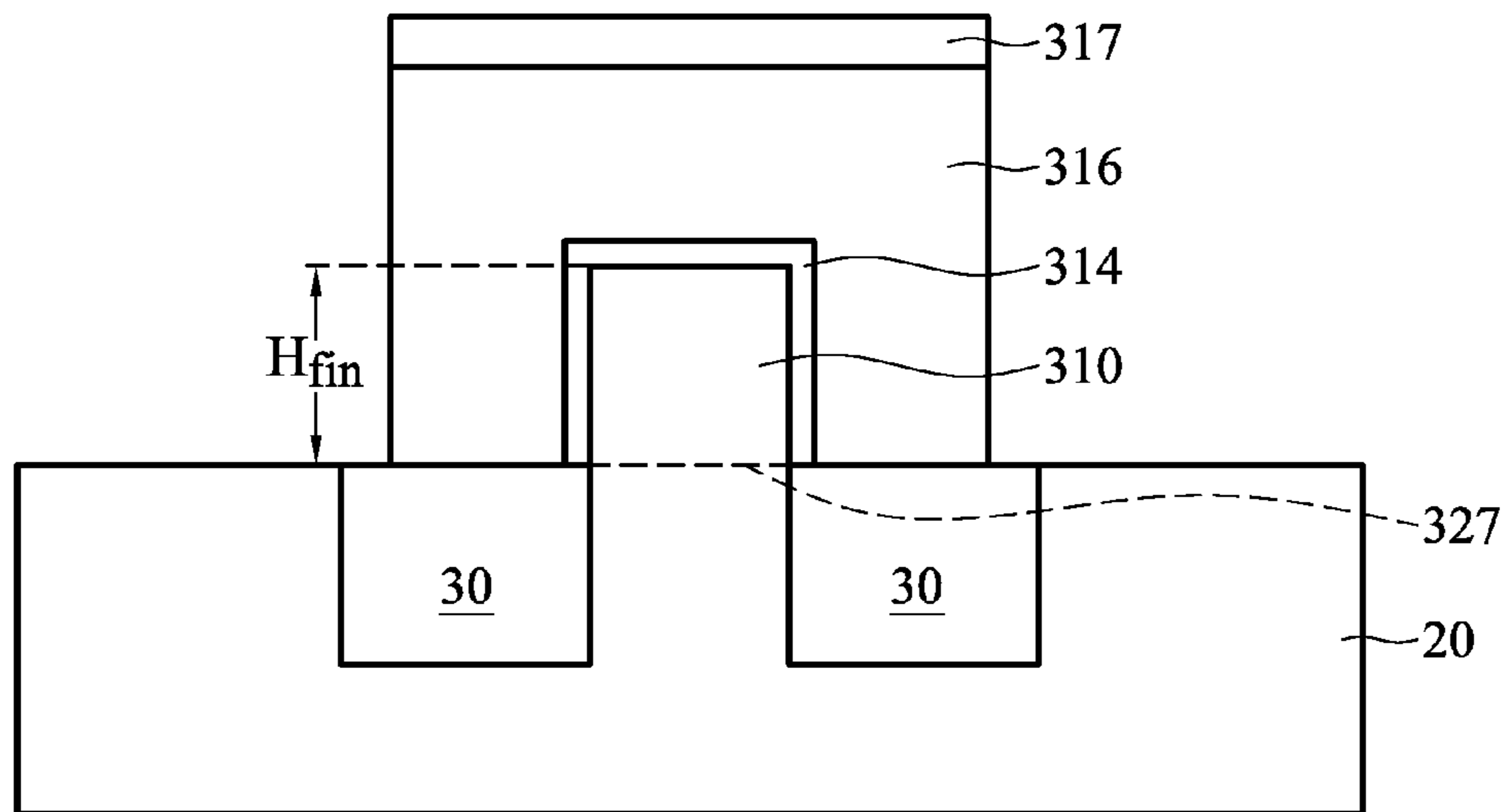


FIG. 15B

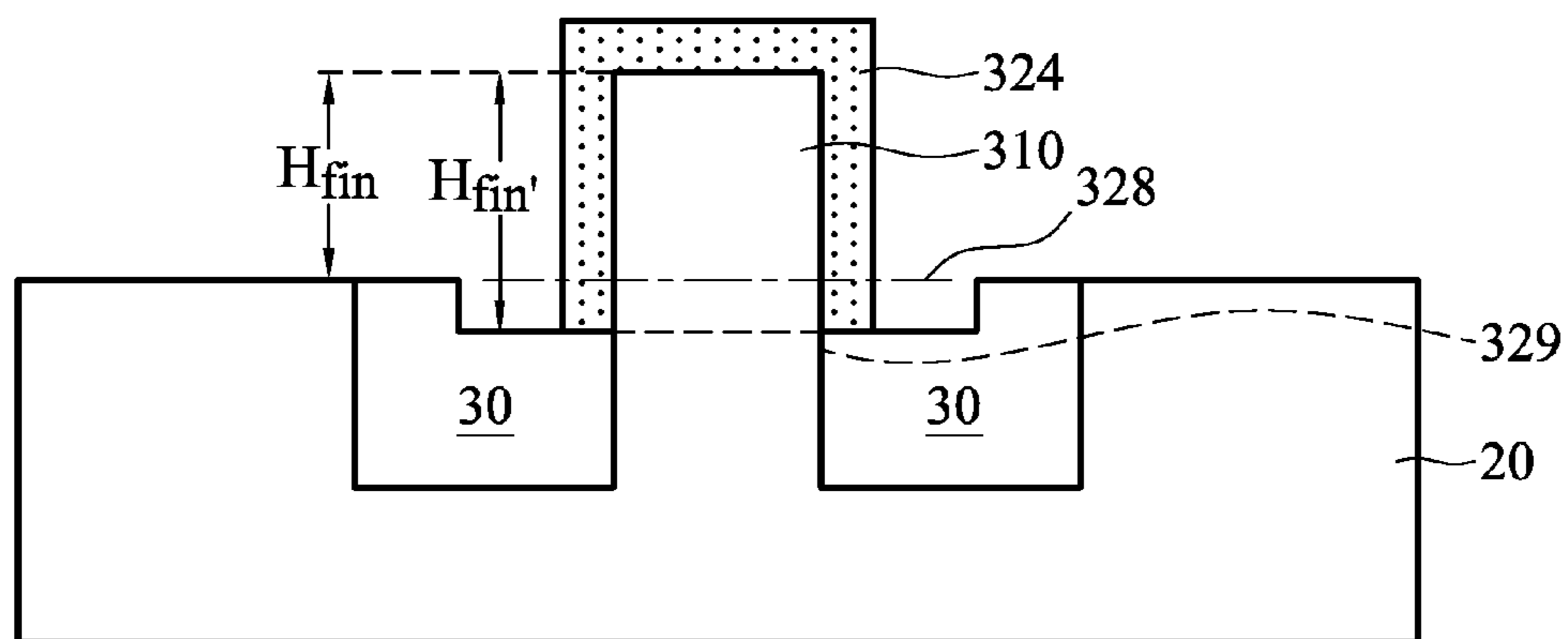


FIG. 15C

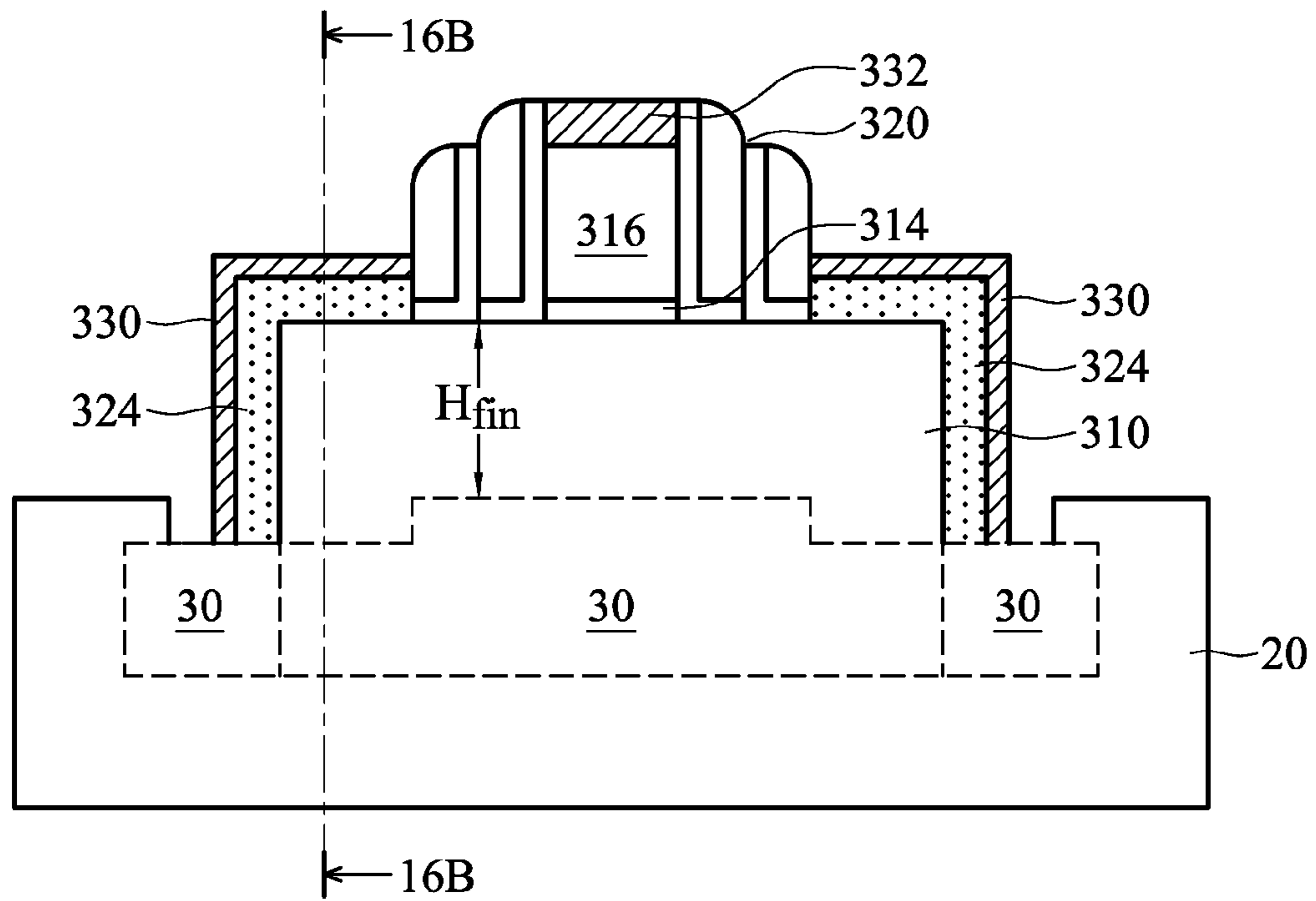


FIG. 16A

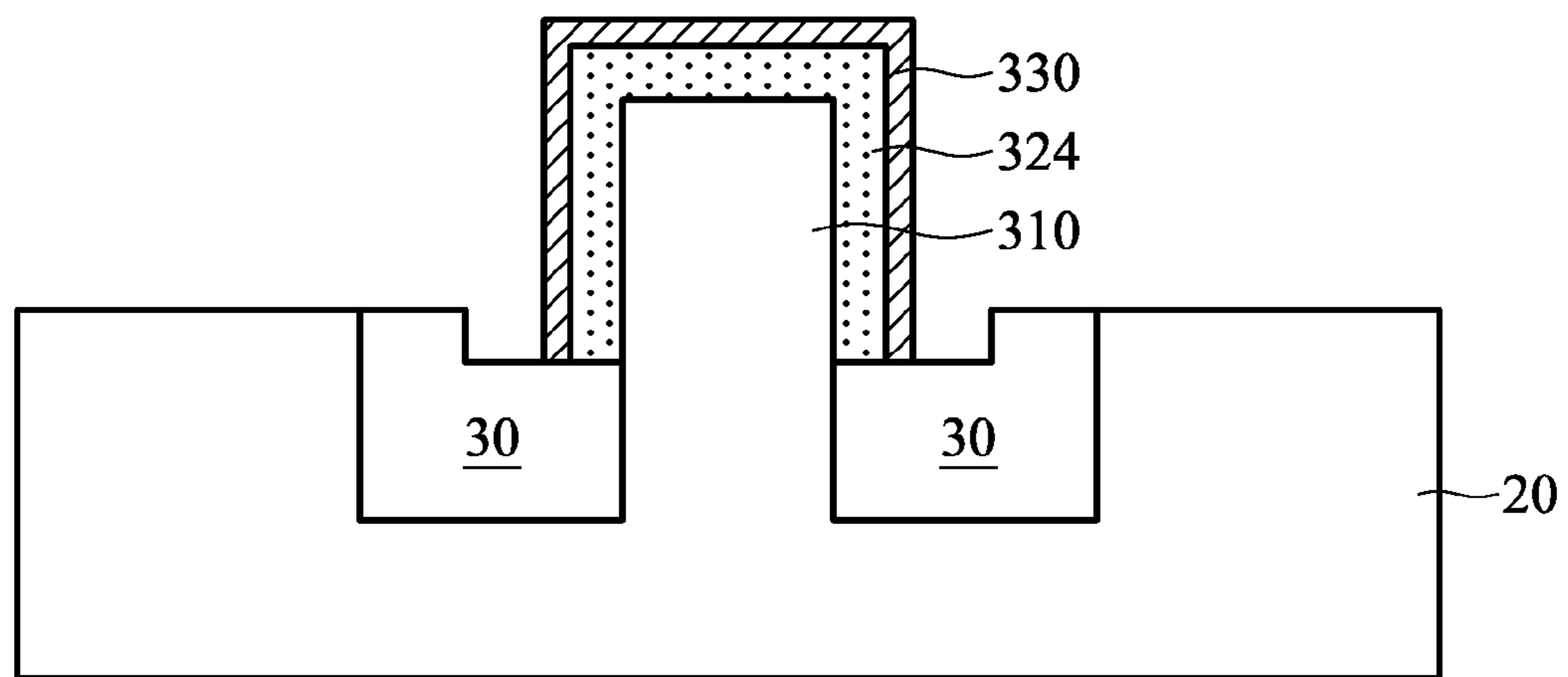


FIG. 16B

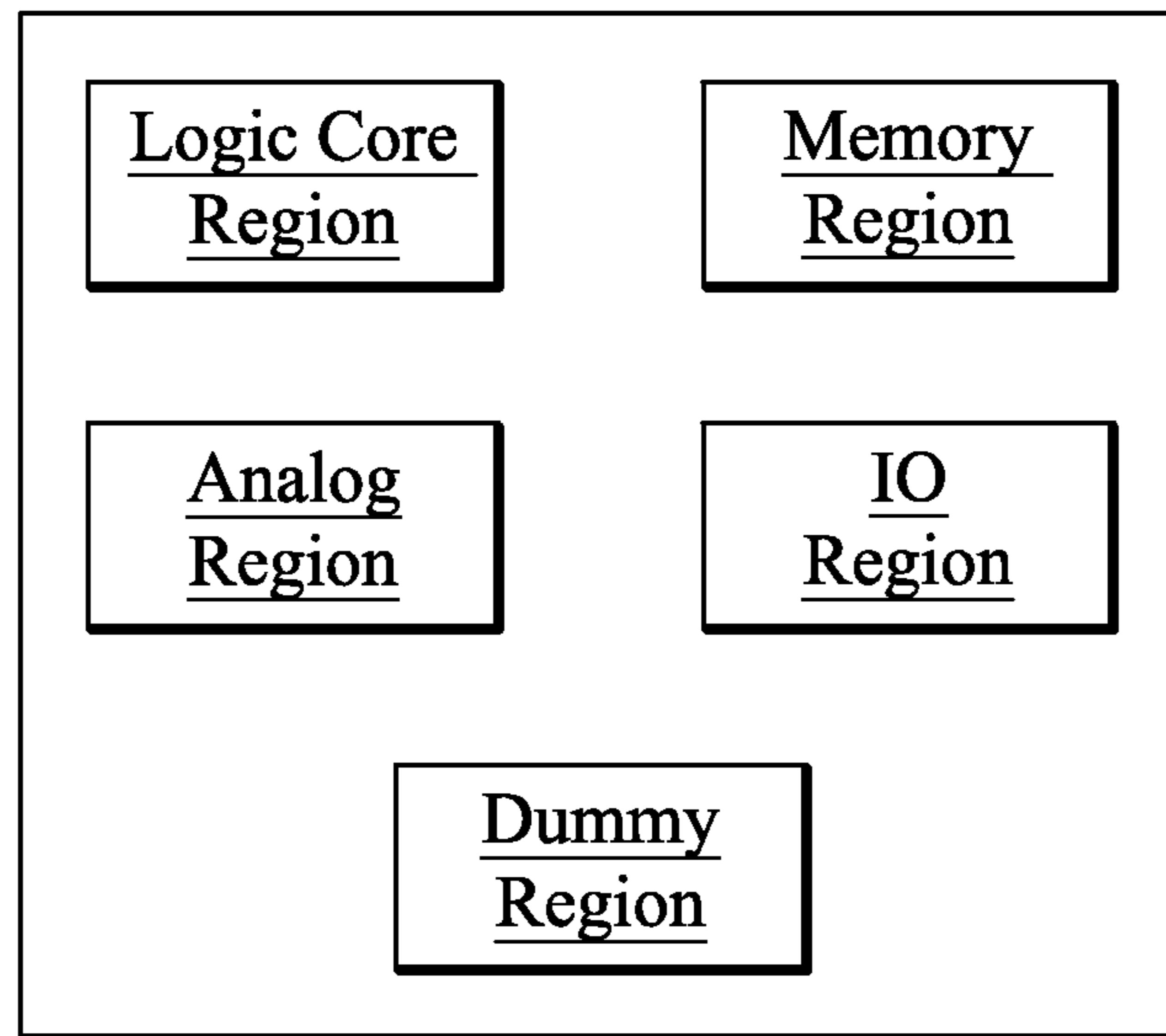


FIG. 17

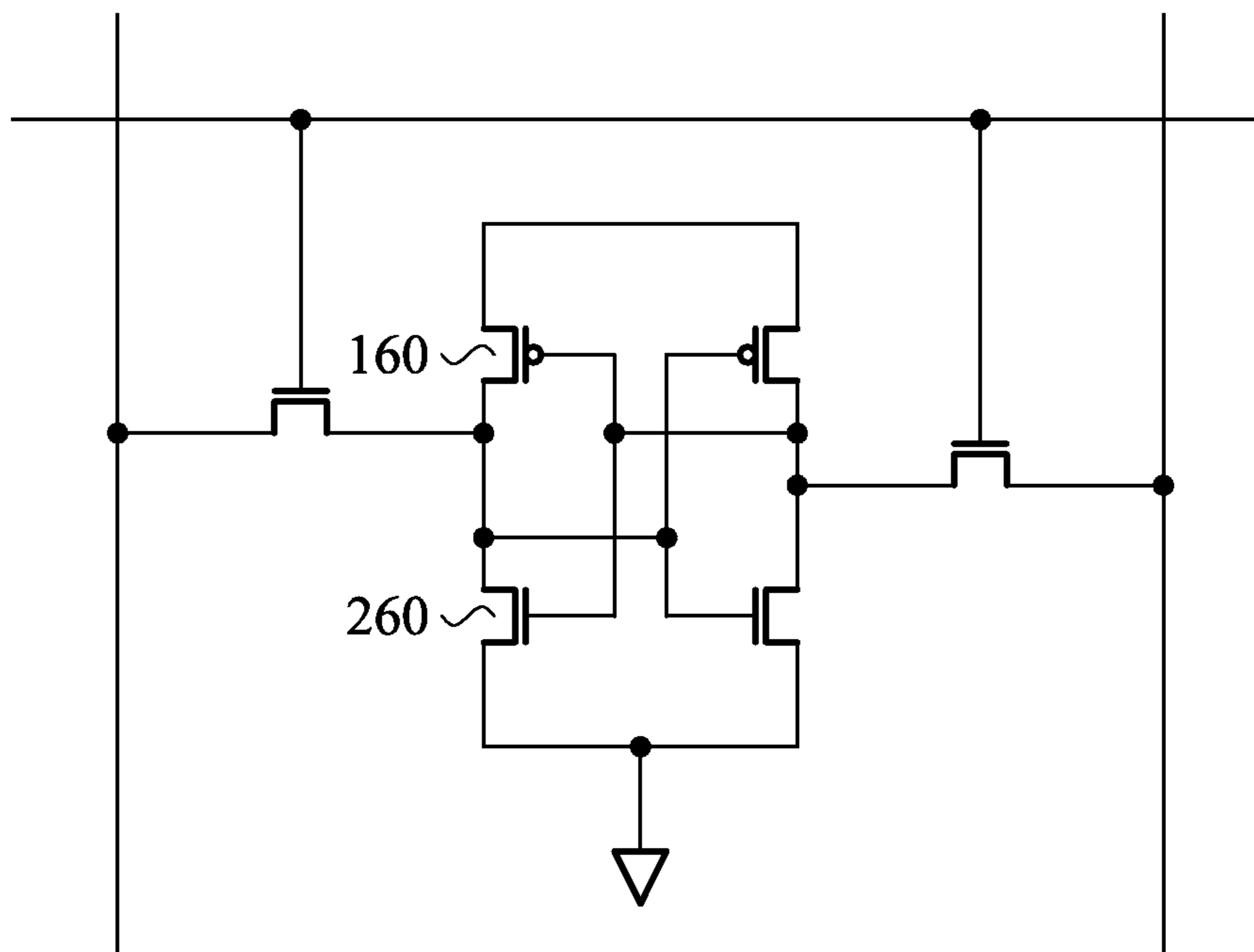


FIG. 18

FINFETS WITH DIFFERENT FIN HEIGHTS

This application is a continuation of, and claims the benefit of, U.S. patent application Ser. No. 12/871,655, filed on Aug. 30, 2010, titled "FinFETs with Different Fin Heights," which claims the benefit of U.S. Provisional Application No. 61/263,164 filed on Nov. 20, 2009, entitled "FinFETs with Different Fin Heights," which applications are hereby incorporated herein by reference.

TECHNICAL FIELD

This application relates generally to integrated circuits, and more particularly to semiconductor fins and Fin field-effect transistors (FinFETs) and methods for forming the same.

BACKGROUND

With the increasing down-scaling of integrated circuits and increasingly demanding requirements for a higher speed of integrated circuits, transistors need to have higher drive currents with increasingly smaller dimensions. Fin field-effect transistors (FinFETs) were thus developed. FinFETs have increased channel widths because the channels include side-wall portions in addition to the portions on the top surfaces of the fins. Since the drive currents of transistors are proportional to the channel widths, the drive currents of FinFETs are increased over that of planar transistors.

SUMMARY

In accordance with one aspect of the embodiment, an integrated circuit structure includes a semiconductor substrate including a first portion in a first device region, and a second portion in a second device region. A first semiconductor fin is over the semiconductor substrate and has a first fin height. A second semiconductor fin is over the semiconductor substrate and has a second fin height. The first fin height is greater than the second fin height.

Other embodiments are also disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the embodiments, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIGS. 1 through 10 are cross-sectional views of intermediate stages in the manufacturing of semiconductor fins having different fin heights in accordance with an embodiment;

FIGS. 11A through 16B are cross-sectional views and perspective views of intermediate stages in the manufacturing of a FinFET in accordance with another embodiment;

FIG. 17 illustrates device regions in a semiconductor chip; and

FIG. 18 illustrates a static random access memory including two FinFETs with fins having different fin heights.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The making and using of the embodiments of the disclosure are discussed in detail below. It should be appreciated, however, that the embodiments provide many applicable inventive concepts that can be embodied in a wide variety of specific contexts. The specific embodiments discussed are

merely illustrative of specific ways to make and use the embodiments, and do not limit the scope of the disclosure.

A novel method for forming semiconductor fin(s) with different fin heights and fin field-effect transistor(s) (FinFETs) is provided. The intermediate stages in the manufacturing of an embodiment are illustrated. The variations of the embodiment are discussed. Throughout the various views and illustrative embodiments, like reference numbers are used to designate like elements.

Referring to FIG. 1, semiconductor substrate 20 is provided. In an embodiment, semiconductor substrate 20 includes silicon. Other commonly used materials, such as carbon, germanium, gallium, arsenic, nitrogen, indium, and/or phosphorus, and the like, may also be included in semiconductor substrate 20.

Semiconductor substrate 20 includes a portion in device region 100 and a portion in device region 200. In an embodiment, device regions 100 and 200 are different regions selected from the group consisting essentially of a logic core region, a memory region (such as an embedded static random access memory (SRAM) region), an analog region, an input/output (10, also referred to as a peripheral) region, a dummy region (for forming dummy patterns), and the like. The above-referenced device regions are schematically illustrated in FIG. 17. In an exemplary embodiment, device region 100 is a logic core region, while device region 200 is an IO region. In alternative embodiments, device region 100 is a p-type FinFET region, while device region 200 is an n-type FinFET region.

Pad layer 22 and mask layer 24 may be formed on semiconductor substrate 20. Pad layer 22 may be a thin film comprising silicon oxide formed, for example, using a thermal oxidation process. Pad layer 22 may act as an adhesion layer between semiconductor substrate 20 and mask layer 24. Pad layer 22 may also act as an etch stop layer for etching mask layer 24. In an embodiment, mask layer 24 is formed of silicon nitride, for example, using low-pressure chemical vapor deposition (LPCVD). In other embodiments, mask layer 24 is formed by thermal nitridation of silicon, plasma enhanced chemical vapor deposition (PECVD), or plasma anodic nitridation. Mask layer 24 is used as a hard mask during subsequent photolithography processes.

STI regions 30 (denoted as 30_1 and 30_2) are formed in substrate 20. The depth of STI regions 30 may be between about 100 nm and about 250 nm, although different depths are also applicable. It is realized, however, that the dimensions recited throughout the description are merely examples, and may be changed if different formation technologies are used. The formation of STI regions 30 may be performed using known methods, hence the process details are not described in detail herein.

Referring to FIG. 2, device region 100 is masked by photo resist 134, leaving device region 200 exposed. The exposed STI regions 30_2 are then recessed through an etching step, resulting in recesses 236 in substrate 20. The resulting structure is shown in FIG. 3. The portions of semiconductor substrate 20 between recesses 236 thus become fins 238, which has a fin height denoted as H_{fn2} . In an exemplary embodiment, fin height H_{fn2} is between 15 nm and about 30 nm, although it may also be greater or smaller. Photo resist 134 is then removed.

Referring to FIG. 4, device region 200 is masked by photo resist 234, leaving device region 100 exposed. The exposed STI regions 30_1 are then recessed through an etching step, resulting in recesses 136, as is shown in FIG. 5. The portions of semiconductor substrate 20 between recesses 136 thus become fins 138, which has a fin height denoted as H_{fn1} . In an

3

exemplary embodiment, fin height H_{fin1} is between 25 nm and about 40 nm, although it may also be greater or smaller. Fin heights H_{fin1} and H_{fin2} are different from each other. The fin height difference ($H_{fin2} - H_{fin1}$) may be greater than about 5 nm, or even greater than about 10 nm. Further, a ratio of H_{fin1}/H_{fin2} may be greater than about 1.25, or even greater than about 1.33.

Next, as shown in FIG. 6, mask layer 24 and pad layer 22 are removed. Mask layer 24, if formed of silicon nitride, may be removed by a wet process using hot H_3PO_4 , while pad layer 22 may be removed using diluted HF acid, if formed of silicon oxide. It is noted that in the structure shown in FIG. 6, the portion of substrate 20 below the bottoms of STI regions 30 may be treated as a semiconductor substrate, while fins 138 and 238 may be treated as being over the semiconductor substrate.

FIG. 7 illustrates the formation of FinFETs 160 and 260 in device regions 100 and 200, respectively. First, well dopants are introduced into the exposed fins 138 and 238, for example, by implantations. In the embodiment in which device region 100 is a p-type FinFET region and device region 200 is an n-type FinFET region, an n-type impurity implantation is performed to dope an n-type impurity such as phosphorous into fins 138, and a p-type impurity implantation is performed to dope a p-type impurity such as boron into fins 238. Gate dielectrics 150 and 250 are formed to cover the top surface and sidewalls of fins 138 and 238, respectively. Gate dielectrics 150 and 250 may be formed by thermal oxidation, and hence may include thermal silicon oxide. Gate electrodes 152 and 252 are then formed on gate dielectrics 150 and 250, respectively. In an embodiment, each of gate electrodes 152 and 252 covers more than one of fins 138 and 238, so that each of the resulting FinFETs 160 and 260 comprises more than one fin 138 and 238, respectively. In alternative embodiments, each of fins 138 and/or 238 may be used to form one FinFET. The remaining components of FinFETs 160 and 260, including source and drain regions and source and drain silicides (not shown), are then formed. The formation processes of these components are known in the art, and hence are not repeated herein.

FIGS. 8 through 10 illustrate an alternative embodiment. The initial structure used in this embodiment is similar to what is shown in FIG. 1. Next, referring to FIG. 8, after the formation of photo resist 234 for region 200, a first implantation is performed with a first dosage to introduce a first impurity into STI regions 30_1. The resulting STI regions 30_1 have a first impurity concentration. Next, as shown in FIG. 9, photo resist 234 is removed, and photo resist 134 is formed. A second implantation is performed with a second dosage to introduce a second impurity into STI regions 30_2. The resulting STI regions have a second impurity concentration. In an exemplary embodiment, the first impurity includes phosphorous, while the second impurity includes boron.

Next, as shown in FIG. 10, photo resist 134 is removed, and STI regions 30 are recessed, for example, using a wet etch or other methods. Due to the different impurity concentrations in STI regions 30_1 and 30_2, the etching rates of STI regions 30_1 and 30_2 are different, and hence the resulting fin heights H_{fin1} and H_{fin2} are different. The difference in fin heights H_{fin1} and H_{fin2} may be further increased by making the pattern density of STI regions 30_1 different from the pattern density of STI regions 30_2 in order to introduce a pattern-loading effect, so that the difference in etching rates of STI regions 30_1 and 30_2 is further increased. In alternative 65

4

is different from that of STI regions 30_2, and the pattern-loading effect is used to result in the fin height difference.

In subsequent steps, hard mask 24 and pad layer 22 are removed, resulting in the structure shown in FIG. 6. Processes are then continued to form FinFETs 160 and 260, as shown in FIG. 7.

By differentiating fin heights in different device regions, the junction window is increased, which means that the fin heights of FinFETs in different device regions are no longer tied together. With the FinFETs in different device regions having different fin heights, it is easier to tune the performance of devices in different device regions. Further, in the embodiment wherein FinFET 160 (FIG. 7) in device region 100 is a p-type FinFET and FinFET 260 in device region 200 is an n-type FinFET, the resulting fin height of p-type FinFET 160 is greater than the fin height of n-type FinFET 260. Accordingly, p-type FinFET 160 and n-type FinFET 260 may be used in a same SRAM cell (FIG. 18). For example, p-type FinFET 160 may be a pull-up transistor, and n-type FinFET 260 may be a pull-down transistor. The greater fin height H_{fin1} of p-type FinFET 160 may compensate for the lower hole mobility compared to the higher electron mobility of n-type FinFET 260. The performance of p-type FinFET 160 and the performance of n-type FinFET 260 may thus be balanced.

FIGS. 11A through 16B illustrate intermediate stages in the manufacturing of a FinFET in accordance with yet another embodiment, wherein the difference in the recessing depths of STI regions 30 are applied to a single FinFET. First, referring to FIGS. 11A and 11B, semiconductor fin 310, which may be a silicon fin formed of the same material as the underlying substrate 20, is formed. The formation of semiconductor fin 310 may be essentially the same as the formation of fins 138 or 238 in FIGS. 2 through 6. FIG. 11A illustrates a lengthwise cross-section view, wherein the dotted lines indicate that fin 310 and substrate 20 are connected through a semiconductor strip. FIG. 11B illustrates a widthwise cross-section view. The fin height of semiconductor fin 310 is H_{fin} , and the fin width of fin 310 is W_{fin} .

Next, as shown in FIG. 12, which is a perspective view, gate dielectric 314 and gate electrode 316 are formed. Gate dielectric 314 is formed on the top surface and sidewalls of fin 310. Gate electrode 316 is formed on gate dielectric 314. Lightly doped source and drain (LDD) regions (not shown) may then be formed by implanting semiconductor fin 310. In an embodiment, slim spacers 318 as shown in FIG. 13 may be formed on the sidewalls of gate dielectric 314 and gate electrode 316, wherein LDD regions may be formed before or after the formation of slim spacers 318. Optionally, mask layer 317, which may be formed of a nitride, is formed. FIG. 13 also illustrates mask layer 317.

Next, as shown in FIG. 14A, gate spacers 320 are formed. Gate spacers 320 may include the previously formed slim spacers 318. It is realized that gate spacers 320 may have many different variations. For example, as shown in FIG. 14A, each gate spacer 320 may have a nitride-oxide-nitride-oxide (NONO structure). In alternative embodiments, each gate spacer 320 may only have a nitride layer on an oxide layer (referred to as a NO structure). The exposed portions of STI regions on opposite sidewalls of semiconductor fin 310 that is not covered by gate electrode 316 are recessed. A perspective view of the structure shown in FIG. 14A is shown in FIG. 14B. To clearly illustrate the heights of fin 310, gate spacers 320 are not shown. In the resulting structure, fin 310 has two heights. The portion of fin 310 (which also includes the channel region of the resulting FinFET) covered by gate spacers 320 and gate electrode 316 has fin height H_{fin} , which fin height is the same as shown in FIG. 11B. As the result of

5

the recessing of STI regions **30**, the portions of semiconductor fin **310** that are not covered have an increased fin height $H_{fin'}$. In an embodiment, $H_{fin'}$ is greater than fin height H_{fin} by greater than about 2 nm, or even greater than about 10 nm. Alternatively, a ratio $H_{fin'}/H_{fin}$ may be greater than about 1.05, and may even be greater than about 1.08, or between about 1.05 and about 1.5.

Next, as shown in FIG. **15A**, epitaxial semiconductor layers **324** are epitaxially grown on the exposed portions of semiconductor fin **310**. Epitaxial semiconductor layers **324** may comprise silicon, germanium, carbon, and/or other known semiconductor materials. In an embodiment wherein the resulting FinFET is of p-type, epitaxial semiconductor layers **324** may comprise silicon and possibly germanium in addition to silicon. In alternative embodiments wherein the resulting FinFET is of n-type, epitaxial semiconductor layers **324** may comprise silicon and possibly carbon in addition to silicon. Thickness T of epitaxial semiconductor layers **324** may be greater than about 10 nm.

FIG. **15B** illustrates an additional cross-sectional view of the structure shown in FIG. **15A**, wherein the cross-sectional view is obtained from the vertical plane crossing line **15B-15B** in FIG. **15A**. Fin height H_{fin} is marked in FIG. **15B**. FIG. **15C** illustrates an additional cross-sectional view of the structure shown in FIG. **15A**, wherein the cross-sectional view is obtained from the vertical plane crossing line **15C-15C** in FIG. **15A**. Fin height $H_{fin'}$ is marked in FIG. **15C**. Comparing FIGS. **15B** and **15C**, it is observed that due to the increased fin height $H_{fin'}$, the volume of epitaxial semiconductor layers **324** is increased. If the fin height of semiconductor fin **310** is not increased from value H_{fin} to value $H_{fin'}$, epitaxial semiconductor layers **324** would have been limited in the region over dotted line **328**. In FIGS. **15B** and **15C**, although there is no clear visible bottoms, semiconductor fins **310** are considered to have bottoms level with top surfaces of STI regions **30** on opposite sides of respective fin portions **310**. Accordingly, as shown in FIG. **15B**, the bottom of the portion of semiconductor fin **310** directly under electrode **316** illustrated as line **327**, and in FIG. **15C**, the bottom of the portion of semiconductor fin **310** not covered by gate electrode **316** and gate spacers **320** is illustrated as line **329**. Bottom **329** is lower than bottom **327**.

Referring to FIG. **16A**, implantations are performed to form source and drain regions (not shown) in semiconductor fin **310** and epitaxial semiconductor layers **324**. Hard mask **317** is also removed, and source/drain silicide regions **330** and gate silicide region **332** are formed on epitaxial semiconductor layers **324**. The formation of the source and drain regions and silicide regions **330** may adopt known methods. After the formation of silicide regions **330** and **332**, epitaxial semiconductor layers **324** may be fully, or partially, consumed. In the resulting structure, silicide regions **330** may be separated from semiconductor fin **310** by remaining portions of epitaxial semiconductor layers **324**, or contact fin **310** directly.

FIG. **16B** illustrates an additional cross-sectional view of the structure shown in FIG. **16A**, wherein the cross-sectional view is obtained from the vertical plane crossing line **16B-16B** in FIG. **16A**. It is observed that by recessing STI regions **30** before the epitaxial formation of epitaxial semiconductor layers **324**, the volume of the source and drain regions is increased. This has the positive effect of reducing the current crowding in the source and drain regions. The desirable tensile or compressive stress applied to the channel region of the resulting FinFET is also increased due to the increased volume of stressed source and drain regions. In addition, since the size of silicide regions **330** is also increased due to the

6

increased sidewall areas of epitaxial semiconductor layers **324**, the current crowding effect in silicide regions **330** is also reduced.

Although the embodiments and their advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the embodiments as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, and composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed, that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the disclosure. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps. In addition, each claim constitutes a separate embodiment, and the combination of various claims and embodiments are within the scope of the disclosure.

What is claimed is:

1. A method comprising:

forming a first shallow trench isolation (STI) region and a second STI region in a semiconductor substrate, the first STI region being in a first device region, and the second STI region being in a second device region;

forming a first mask covering the second device region; recessing the first STI region to a first depth, a portion of the semiconductor substrate extending from the recessed first STI region forming a first semiconductor fin, the first depth being from a top surface of the first semiconductor fin to a top surface of the recessed first STI region; removing the first mask;

forming a second mask covering the first device region; and recessing the second STI region to a second depth different from the first depth, a portion of the semiconductor substrate extending from the recessed second STI region forming a second semiconductor fin, the second depth being from a top surface of the second semiconductor fin to a top surface of the recessed second STI region, a portion of the semiconductor substrate being between the first semiconductor fin and the second semiconductor fin, top surfaces of the first semiconductor fin, the second semiconductor fin, and the portion of the semiconductor substrate being level with each other.

2. The method of claim 1 further comprising:

removing the second mask;

forming a first gate dielectric and a second gate dielectric on top surfaces and sidewalls of the first semiconductor fin and the second semiconductor fin, respectively; and forming a first gate electrode and a second gate electrode on the first gate dielectric and the second gate dielectric, respectively, the first semiconductor fin, the first gate dielectric, and the first gate electrode forming a first fin field-effect transistor (FinFET), and the second semiconductor fin, the second gate dielectric, and the second gate electrode forming a second FinFET.

3. The method of claim 2, wherein the first FinFET and the second FinFET are FinFETs of a same static random access memory cell.

4. The method of claim 2, wherein the first FinFET is a p-type FinFET and the second FinFET is an n-type FinFET.

7

5. The method of claim 1, wherein the difference between the first depth and the second depth is greater than about 5 nm.

6. The method of claim 1, wherein a ratio of the first depth to the second depth is greater than about 1.25.

7. The method of claim 1, wherein the first STI region has a bottom surface level with a bottom surface of the second STI region.

8. The method of claim 1, wherein the first depth is greater than the second depth.

9. A method comprising:

forming a first shallow trench isolation (STI) region and a second STI region in a semiconductor substrate, the first STI region being in a first device region, and the second STI region being in a second device region;

doping the first STI region with a first impurity to a first impurity concentration;

doping the second STI region with a second impurity to a second impurity concentration different from the first impurity concentration; and

simultaneously recessing the first STI region and the second STI region, a portion of the semiconductor substrate extending from the recessed first STI region forming a first semiconductor fin, and a portion of the semiconductor substrate extending from the recessed second STI region forming a second semiconductor fin.

10. The method of claim 9, wherein the first semiconductor fin has a first fin height from a top surface of the recessed first STI region to a top surface of the first semiconductor fin, and wherein the second semiconductor fin has a second fin height from a top surface of the recessed second STI region to a top surface of the second semiconductor fin, the second fin height being different than the first fin height.

11. The method of claim 10, wherein first fin height is greater than the second fin height.

12. The method of claim 10, wherein a ratio of the first fin height to the second fin height is greater than about 1.25.

13. The method of claim 10, wherein a difference between the first fin height and the second fin height is greater than about 5 nm.

14. The method of claim 9 further comprising:

forming a first gate dielectric and a second gate dielectric on top surfaces and sidewalls of the first semiconductor fin and the second semiconductor fin, respectively; and

forming a first gate electrode and a second gate electrode on the first gate dielectric and the second gate dielectric, respectively, the first semiconductor fin, the first gate dielectric, and the first gate electrode forming a first fin field-effect transistor (FinFET), and the second semiconductor fin, the second gate dielectric, and the second gate electrode forming a second FinFET.

15. The method of claim 14, wherein the first FinFET is a p-type FinFET, and the second FinFET is an n-type FinFET, and wherein the first FinFET and the second FinFET are FinFETs of a same static random access memory cell.

16. The method of claim 9, wherein the first device region and the second device region are different types of regions selected from the group consisting essentially of a logic core region, a memory region, an analog region, an input/output (IO) region, and a dummy region.

8

17. A method comprising:

forming a first shallow trench isolation (STI) region and a second STI region in a semiconductor substrate, the first STI region being in a first device region, and the second STI region being in a second device region, a first portion of the semiconductor substrate extending from the first STI region forming a first semiconductor fin, and a second portion of the semiconductor substrate extending from the second STI region forming a second semiconductor fin, the first STI region having a first depth from a top surface of the first STI region to a bottom surface of the first STI region, the second STI region having a second depth from a top surface of the second STI region to a bottom surface of the second STI region, the second depth being different than the first depth, a portion of the semiconductor substrate being between the first semiconductor fin and the second semiconductor fin;

forming a first gate dielectric and a second gate dielectric on top surfaces and sidewalls of the first semiconductor fin and the second semiconductor fin, respectively; and

forming a first gate electrode and a second gate electrode on the first gate dielectric and the second gate dielectric, respectively, the first semiconductor fin, the first gate dielectric, and the first gate electrode forming a first fin field-effect transistor (FinFET), and the second semiconductor fin, the second gate dielectric, and the second gate electrode forming a second FinFET.

18. The method of claim 17, wherein the forming the first STI region and the second STI region comprises:

forming a first mask covering the second device region, wherein the first device region is not covered by the first mask;

recessing the first STI region to a first depth, wherein the first portion of the semiconductor substrate adjoining a removed portion of the first STI region forms the first semiconductor fin;

removing the first mask;

forming a second mask covering the first device region, wherein the second device region is not covered by the second mask; and

recessing the second STI region to a second depth different from the first depth, wherein the second portion of the semiconductor substrate adjoining a removed portion of the second STI region forms the second semiconductor fin.

19. The method of claim 17, wherein the forming the first STI region and the second STI region comprises:

doping the first STI region with a first impurity to a first impurity concentration;

doping the second STI region with a second impurity to a second impurity concentration different from the first impurity concentration; and

simultaneously recessing the first STI region and the second STI region.

20. The method of claim 17, wherein top surfaces of the first gate electrode and the second gate electrode are level with each other.

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